

Selecting a Differential Amplifier

DYNAMICSTM

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By Ralph Morrison, President

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WHAT DO THEY DO?

A commonly-encountered problem in instrumentation is the amplification of a signal where differences of ground potential can cause signal contamination. A difference of ground potential is often called common-mode voltage, and instruments used to amplify signals in the presence of such common-mode voltages are called "differential amplifiers".

SHIELDING - AN ELEMENTARY CONCEPT, BASIC TO INSTRUMENTATION

The most elementary ideas of shielding are helpful in understanding how common-mode signals are treated in differential amplifiers. If a circuit is completely enclosed within a single shield, the presence of all other external potentials cannot influence the circuit within the shield. True, they can cause currents to flow in the shield, but if the shield is a good conductor the influence, internally, will be negligible.

To insure that the circuit within the shield will operate satisfactorily, the shield is tied to the zero signal point of the circuit. If this is not done, the shield acts as a very complicated parasitic capacitance, coupling all parts of the internal circuit to all other parts with resulting difficulties.

When the signal reference zero is grounded or tied once to some external structure or to a point for observation, the potential of the signal zero is now known. If the input circuitry is grounded or associated with one potential and the output circuitry is grounded or associated with another, a difference of potential is impressed between two points, both of which are called "signal zero". This difference of potential will have no influence if it can be kept from causing currents to flow in any part of the source impedance. If this potential difference causes even a few nanoamperes of current to flow in the input circuitry, unwanted pickup usually results.

GUARD SHIELD METHOD OF COMMON-MODE REJECTION

If the input circuits are to be shielded by a zero signal potential, and the output circuits are to be shielded by another zero signal potential, some means of coupling the two circuits is required. One very effective means of providing this coupling involves a transformer. Figure 1 shows such a transformer as the coupling element for a modulator and demodulator placed in the signal path.

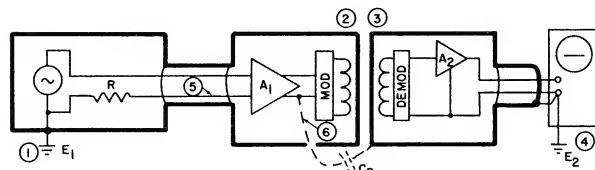


Figure 1. Guard Shield Common-Mode Rejection

This technique places the common-mode signal or ground difference of potential $E_1 - E_2$ between transformer shields. If the shields were perfect, no common-mode currents would flow in signal conductors. The only path for current would be ①-②-③-④-①. This method of rejecting the common-mode signal is called the Guard Shield method. The input shield, or guard, surrounds the input preamplifier as well as the input leads.

The input shield or guard is, of course, never perfect. If, for purposes of analysis, the total leakage capacitance from all input signal points to all external grounds is lumped into one capacitance, a simple calculation will indicate what value of capacitance can be tolerated. Capacitance C_2 in Figure 1 will permit current to follow the path ①-⑥-③-④-①. If R is 1000 ohms, and a current below 10 na at 60 cps is desired, C_2 must be less than 2 picofarads. This represents an impedance of 1000 megohms.



About the author...Ralph Morrison writes and lectures extensively in the field of Instrumentation. A lifelong interest in the special problems of low level signal amplification led to pioneering in the development of multiple feedback loop dc amplifiers. Instrumentation hardware of his design has been used on space vehicles and in ground support equipment of the major space exploration programs, notably Ranger and Mariner.

A graduate of both California Institute of Technology (BS Physics) and University of Southern California (MS Electrical Engineering), Mr. Morrison was one of the original founders of Dynamics Instrumentation Company. He is a member of I.E.E.E. and a Past President of the Los Angeles Electronic Club.

The division of gain between A_1 and A_2 in Figure 1 is a function of the amplifiers' design. Designs exist where either A_1 or A_2 is unity. Designs also exist where A_1 and/or A_2 are entirely passive. These features, while important in terms of specifications, are not germane to describing the principles of differential amplifier operation.

The next section describes the design approach where A_1 is reduced (in theory) to the ultimate limit: a shielded pair of wires.

ELECTRONIC METHOD OF COMMON-MODE REJECTION

If common-mode voltages are processed electronically with a gain approaching zero, and the difference signal is processed for amplification, the result is a differential amplifier with common-mode rejection. Figure 2 shows an elementary circuit approach which has these qualities.

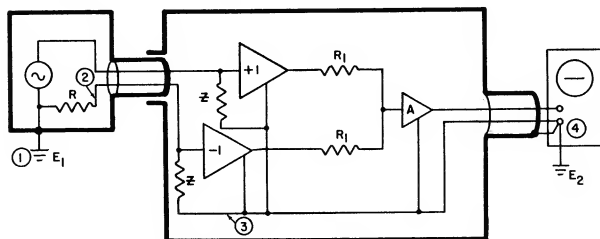


Figure 2. Electronic Common-Mode Rejection

In this technique, the potential difference $E_1 - E_2$ causes current to flow in the source resistance R through the input impedances Z of the input amplifiers. The path is ①→②→③→④→①. It is of interest to calculate just how large Z must be. Consider $E_1 - E_2 = 10$ volts, the gain is 1000 and $R = 1000$ ohms. If the error limit is 0.1%, the current flow in R must be below 10 na. This implies that Z must be 1000 megohms or greater.

SOURCE IMPEDANCES

A high input impedance in a differential dc amplifier does not necessarily imply that the amplifier can operate from a high source impedance. As discussed above, a high input impedance is required to meet the common-mode rejection specification. Source impedances are usually restricted to a small fraction of this input impedance. For example, a gain 1000 amplifier with a 1000 ohm line unbalance requires a 1000 megohm input impedance to

meet a 120 db common-mode rejection specification. The maximum source impedance recommended by the manufacturer could be 1000 ohms. This is one millionth of the input impedance. Amplifiers that can operate from high source impedances are available but this must be a stated requirement in the design criteria.

SHIELD LEAKAGES

If common-mode potentials cause unwanted current to flow in the source impedance, the error signals produced cannot usually be separated from the desired signals. Input shield leakages can permit just this to occur, irrespective of the type of instrument being used. Figure 3 illustrates the problem. Note that capacitor C_1 parallels the input impedance to the differential amplifier as shown in Figure 2 and parallels the leakage capacitance C_2 as shown in Figure 1.

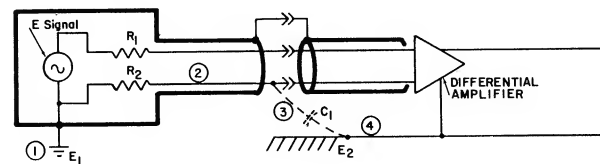


Figure 3. Leakage Capacitance in an Input Shield

The common-mode signal, $E_1 - E_2$, causes current to flow in path ①→②→③→④→①. If $E_1 - E_2$ is 10 volts, $R_1 - R_2$ is 1000 ohms, and the amplifier gain is 1000, then C_1 must be less than 2 pf if the common-mode rejection ratio is to be 120 db at 60 cps. Even at this rejection level, 0.1% errors will result from the presence of the common-mode signal.

N. B. The conclusion to be drawn is that input shields must be tight in the vicinity of unknown grounds. It is a problem basic to operation with differential amplifiers, and is not related to the type of instrument used in the system.

COMMON-MODE REJECTION VERSUS GAIN

Differential amplifiers can be divided into two common-mode rejection categories. In the first, the rejection ratio is a constant for all gains. In the second, the rejection ratio reduces with gain. All Guard-Shield types as shown in Figure 1 are in the first category, but Electronic Method common-mode rejection instruments can be designed both ways.

A constant rejection ratio design involves a more complex instrument, providing an increasing immunity from common-mode error as gain requirements are lowered; e. g., if a 10 volt common-mode level causes a 0.1% error at gain 1000, it will cause a 0.01% error at gain 100. If the rejection ratio reduces with gain, the error will be 0.1% for all gains.

COMMON-MODE REJECTION VERSUS FREQUENCY

A common-mode rejection ratio may be adequate at 60 cps and inadequate at a higher frequency. Many practical situations arise in which the common-mode signals are high frequency in nature. They may be harmonics of 60 cps or some other power frequency. In Figures 1 and 2, it can be seen that C_2 or Z will permit more common-mode current to flow at higher frequencies, with the obvious implication that the rejection ratio falls off as the frequency becomes higher.

These facts are significantly related to the previous discussion. If high frequency common-mode rejection is inadequate at the maximum gain in an instrument that has constant common-mode rejection, operation at lower gains can be within specification. If the instrument has a common-mode rejection ratio that reduces with gain, the performance will be inadequate at all gains if it is inadequate at the maximum gain.

DYNAMIC COMMON-MODE REJECTION

The Guard-Shield approach to common-mode rejection (Figure 1) has the advantage that the common-mode signal is impressed between electrostatic shields and is not electronically processed.

The Electronic Method (Figure 2) does, however, require processing of the common-mode signal and for this reason a variety of difficulties can occur. If the common-mode level is 10 volts and the desired signals are in millivolts, the electronics must be able to process the common-mode signals without limiting, overload or gain change -- independent of frequency. If the electronics fail in this task, the signals will be badly disturbed. Stated another way, the common-mode rejection ratio must be independent of common-mode level and frequency.

The practicalities of modern instrumentation require operation in situations where some of the common-mode signal is rf in nature. A design which overloads or limits in the presence of this common-mode rf is unsatisfactory, hence the design under consideration should be verified for performance under these conditions.

Overloading in differential amplifiers can occur from overscale signals or overscale common-mode levels. The recovery time is a function of design and also of the magnitude of the overscale effect. If the instrument cannot properly respond to higher frequency common-mode signals within its normal voltage bounds, it is in overload, and is properly described as deficient in common-mode slewing capability.

FLOATING SOURCES

The signal source in some applications is not grounded (an ohmic path does not exist through the system from input to output, exclusive of the amplifier). The Guard Shield instruments of Figure 1 are not affected by this form of operation. It is mandatory that the input shield be tied ohmically to the source somewhere, even though the shield and its contents are "floating". This required connection is preferably made at the transducer.

In the Electronic Method, the input ground connection must be more carefully considered. This is because currents required to operate the input circuitry must flow in some ground return path. Obviously, even 0.1 nanoamperes flowing in 10^{10} ohms causes a one volt potential drop. If the source is completely undefined or floating, the input circuitry will assume an average potential determined by the impedance of the leakage path to ground. This assumed potential is common-mode at dc and, for small values, can be ignored. Since these currents do vary as a function of temperature, it is still necessary to treat the problem even if it appears to be solved at room temperature.

In the Electronic Method, field effect devices help a great deal, but a finite current still must flow. To provide a known path that guarantees proper performance without degrading common-mode rejection, a resistance of 10 megohms can be placed between input and output shields. Thus, even if the source is floating, an adequate return path for the input current is guaranteed. With this solution, temperature no longer governs the dc common-mode level and satisfactory floating operation can be maintained.

Floating operation should be avoided, if possible. If it cannot be avoided, the consequences should be carefully weighed. Lines that are not grounded can short to unknown potentials. The resulting hazard may be undetectable because no obvious short circuit or malfunction is created. Floating sources are also subject to transient disturbances, such as lightning, and these disturbances can do damage to instruments connected to these sources.

INPUT ATTENUATORS

Gains below 10 are often realized through the use of input attenuators. Several design choices are available. But, since the instrument's applicability is affected by which design option is selected, it is important that the differences be understood.

Balanced input attenuators are generally desirable; however, for design reasons Guard-Shield amplifiers usually employ unbalanced attenuators which are only referenced to the input or guard shield. No other choice is possible.

In the Electronic Method of common-mode rejection, the input attenuator can be referenced to the input or output circuitry. See Figures 4(a) and 4(b).

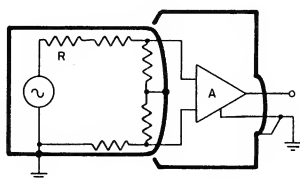


Figure 4(a). Input Attenuator
Referred to the Input

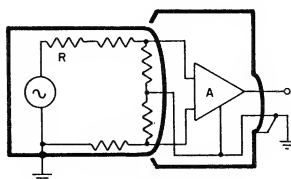


Figure 4(b). Input Attenuator
Referred to the Output

The system in Figure 4(b) adds a common-mode current path between the source and the output ground. It does have the advantage of reducing the common-mode level that must be handled by the amplifier. A 10:1 attenuator will permit a 100 volt common-mode level in an instrument which could only tolerate a 10 volt common-mode level without an attenuator. The current path will, however, reduce the rejection ratio.

The system in Figure 4(a) does not add an additional common-mode current path, and therefore keeps the common-mode rejection ratio high. The common-mode voltage operating level is not affected by the presence of the attenuator. If this level is adequate at gains where the attenuator is not used, the level will also be adequate for gains involving the attenuator.

CONCLUSION

Differential amplifiers have an important place in instrumentation. A wide range of design characteristics are available. Differences exist between common-mode rejection methods and rejection level capabilities. Many operating specifications are dependent on the design technique used. Some of the important parameters are: constancy of common-mode rejection with gain, common-mode slewing and overload characteristics, floating versus grounded source conditions and input attenuator design. Only when these parameters are understood and correctly related to expected performance, is it possible to select the differential amplifier design.

Other papers by Ralph Morrison

- Shielding and Grounding for Instrumentation Systems
- Selecting a Differential Amplifier
- Application Notes for Differential DC Amplifiers
- RC Constant-Argument Driving-Point Admittances

Application notes

Differential amplifiers can be applied to a wide variety of instrumentation problems, but, because of their sophistication, they are easily misapplied.

Differential amplifiers are required where:

1. Both signal source and the amplifier signal must be grounded.
2. The input has resistance to ground on both input lines.
3. Thermocouple signals are to be amplified, and the output is grounded.
4. Common power supplies are used to excite the strain gages.
5. Difference signals above ground must be measured.

The most-often-encountered problems of application are:

1. Proper treatment of the input shield. The shield should be connected to the source, preferably at the source. The location of the source ground should also serve as the point to tie the input shield. The shield should be continuous, with as few openings as possible and tied once to the amplifier and once to the source.

2. Adequate common-mode capability. Instrument capability varies between 10 and 300 volts. If the rejection capabilities are magnitude or frequency limited, the signal is subject to disturbance.

3. Floating input operation. In some designs, the input may be left floating. In other designs, floating operation may be marginal. The input shield should always be tied to the source. Grounding the shield, if the source is floating, is incorrect. If a floating source is necessary, the ground path requirements must be carefully considered.

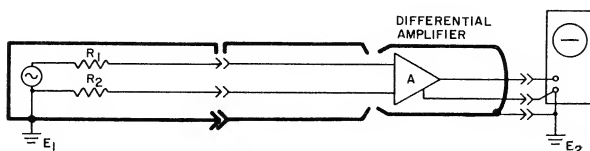


Figure 1
Typical Grounded-Source to Grounded-Output Application

R_1 - R_2 equals the line unbalance. Note how the shield ties to the signal conductors are made at the signal grounding points. E_1 - E_2 is the common-mode voltage.

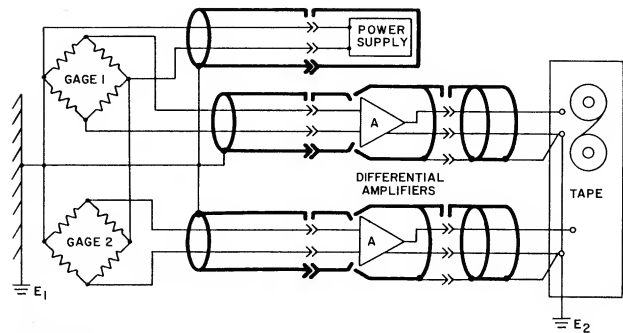


Figure 2
Common Power Supply - Gage Excitation System

A common power supply can be used if the gages are bonded to a structure that does not have a significant voltage gradient on its surface.

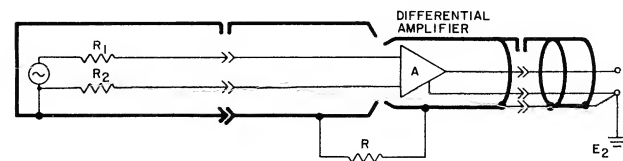


Figure 3
Floating-Source Operation

The ground return path R adds slightly to the current flow in the shield, but will not influence common-mode rejection processes.

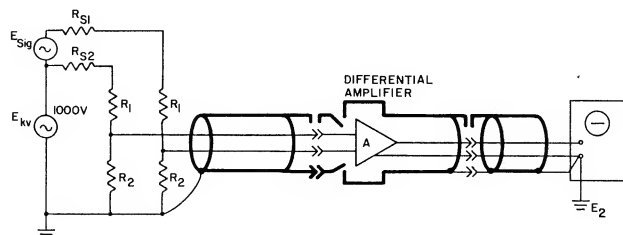


Figure 4
Reduction of Common-Mode Signal by Attenuation

Signals may be inserted into a standard instrument if they can tolerate attenuation. By attenuating the composite signal the common-mode signal E_{kv} can be handled.

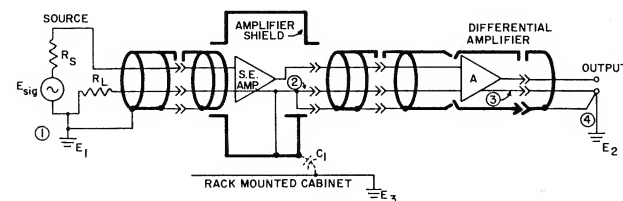


Figure 5
Isolating Single-Ended Amplifiers

A grounded-source amplifier can be isolated through the use of a differential amplifier. Common-mode voltages cause current to flow along the path ①-②-③-④-①. The limiting impedance is the input impedance of the differential amplifier. The voltage drop in R_L caused by this current determines the common-mode rejection. Current also flows in C_1 , if E_1 - E_3 is not kept to a small value.

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